Plasma Science and Technology
Room: Aztec - Session PS-FrM

Liquids and Multiphase Discharges

Moderator: C. Labelle, GLOBALFOUNDRIES

8:20am **PS-FrM1 Dynamic of Plasma Ignition and Propagation in Water**, *W.G. Graham,* Queen's University Belfast, Northern Ireland, ***A. Rousseau***, *P.H. Ceccato, O. Guaitella*, Ecole Polytechnique, France **INVITED**

We present an experimental study of a filamentary microplasma discharge inside liquid water. Such plasmas are used for liquid electrical insulations tests and for pollution control of water [1-2]. It was recently shown that the propagation velocity was found to be surprisingly constant whatever the experimental parameters and especially as a function of the water conductivity [3]. The purpose of the present work is to understand the physical mechanisms responsible for initiation and propagation of the discharge. A point to plane electrode configuration submerged in water has been constructed and was submitted to a high voltage pulse. Filaments inception and propagation and several discharges modes have been characterized with electrical measurements and time resolved nanosecond imaging. A Shadow diagnostic using 2 fast cameras was implemented to study the gas content and the shock wave emission from the discharge. The influence of the applied voltage polarity and the water conductivity was investigated. At positive high voltage the growth of the discharge begins by the nucleation of a microbubble at the needle electrode within a few microseconds at an applied voltage of 40kV, a hemispheric branching filamentary structure grows at 3km/s during 100ns and is followed by the propagation of second filamentary structure ten time faster. This continuous propagation on a nanosecond time scale is followed by a stepwise propagation in case of distilled water. When the filaments reach the opposite electrode electrical breakdown occurs. At negative polarity the discharge is much slower 600m/s. The morphology of the gas cavity is driven by interface instability.

[1] P. Bruggeman et al. 2009, J. Phys. D: Appl. Phys. 42

[2] B. R. Locke et al. Ind. Eng. Chem. Res. 45 882-905

[3] P. Ceccato et al. J. Phys. D: Appl. Phys. 43 (2010) 175202

9:00am **PS-FrM3 Copper Nanoparticles Synthesized by Glow Discharge in Solution**, ***N. Saito***, *Y. Aoki, J. Hieda, O. Takai*, Nagoya University, Japan

Plasma in gas phase is widely used in many industrial fields such as electronic device manufacturing processes (plasma etching, sputtering, plasma-enhanced CVD, etc.), hard coating processes (ion plating, sputtering, etc.), surface treatment processes (low or atmospheric pressure plasma treatments, sputtering, plasma etching, etc.) and so on. Plasma in solid phase has been utilized finally for surface plasmon resonance (SPR) spectroscopy, nanoparticles, etc., and plasmonics is developing as a new research field. On the other hand, plasma in liquid phase is not generally well-known, although it has been partially utilized in water treatments and electrical discharge machining. The fundamentals of plasma in liquid phase have not been established, including its generation techniques, its state, and activated chemical species. However, it would be reasonable to expect a higher reaction rate under lower-temperature conditions, and the greater chemical reaction variability since the molecular density of liquid is much higher than that of gas phase. So we have named the plasma in liquid phase "solution plasma" because we make variety of plasma by choosing the combinations of solvents and solutes in solutions, and are developing solution plasma processing (SPP). In SPP, aqueous solutions, nonaqueous ones, liquid nitrogen, supercritical fluids, etc. can be utilized as solutions. Recently, we have investigated the features of SPP and the applications such as syntheses of nanoparticles and mesoporous silica, and surface modification of particles.

In this research, copper nanoparticles were synthesized by a glow discharge in solution. A pulsed power supply was used to generate discharges. The pulsed width was 2 micro seconds, the repetition frequencies were 10 – 15 kHz. The electrode was tungsten wire in the diameter of 1 mm with electrode gap of 0.3 mm. Ethanol was used as a solution. Monohydroxy copper acetate (II) was utilized as a raw material of copper. The molar concentration of raw material was adjusted to 5mM. Moreover sodium iodide was added to the solution up to 5 mM. The solution and the productants after the discharge were analyzed by 1H NMR, Uv-Vis spectroscopy, XRD, TEM. Finally, TEM showed the synthesis of copper nanoparticles. Moreover 1H NMR show the presence of acetaldehyde in the solution after discharge, which might work as a reducing agent.

9:20am **PS-FrM4 The Consequences of Bubbles in the Electrical Breakdown of Liquids**, ***N.Yu. Babaeva***, *M.J. Kushner*, University of Michigan, Ann Arbor

Streamer discharges in liquids do not likely directly develop through the liquid phase. It is thought that breakdown occurs inside bubbles where streamers preferentially propagate along the surface of the bubbles and near gas–liquid interfaces [1]. In many applications, plasmas are intentionally generated inside bubbles in liquids to produce reactive species which then diffuse through the gas-liquid interface. For short (nanoseconds) time scales, one of the proposed mechanisms for electrical breakdown in liquids is the sequential linking of plasmas in bubbles (PBs). For example, the large E/N produced in the bubble compared to the adjoining liquid enables more rapid breakdown and charging of inner surfaces. If the bubbles are in favorable alignment, the inter-bubble electric field enhancement may provide a mechanism for propagating the streamer through the liquid. On longer timescales (microseconds) when heating of the gas-liquid interface becomes important, thermally induced breakdown likely occurs. The mechanism includes heating and evaporation of adjacent liquid layers, expansion of the gas phase accompanied by the deformation of the gas-liquid interface by electrical forces. In this case the favorable alignment of bubbles does not play an important role.

In this paper, properties of PBs and of streamers intersecting with liquids will be discussed based on results of computer simulations.[2] The model used in this investigation is *nonPDPSIM*, a 2-dimensional plasma hydrodynamics model in which the densities and momentum of charged and neutral particles are solved coincident with Poisson's equation and radiation transport. On short time scales liquids are computationally treated in the same manner as plasma with an appropriate density dependent polarization to provide the liquid density permittivity. On longer time scales, heating and evaporation of the adjacent portions of the liquid is addressed.

We will also address streamers intersecting with liquids in the context of plasma treatment of biological tissue or wounds. In this case the intersection of streamers with the liquid on time scales shorter than the dielectric relaxation time additionally produce electric fields within the underlying tissue. The values of these electric fields, as large as 100s kV/cm, are above the threshold for breakdown for atmospheric pressure gas bubbles or gas filled vacuoles. As such, it may be possible to produce plasmas below the surface of the liquid or within tissues.

[1] P. Bruggeman and C. Leys, J. Phys. D **42,** 053001 (2009).

[2] N. Yu. Babaeva and M. J. Kushner, J. Phys. D **42**, 132003 (2009).

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9:40am **PS-FrM5 Diagnostic Studies of AC-driven Plasmas in Saline Solutions: the Effect of the Frequency on the Plasma Behavior**, ***H.W. Chang***, *C.C. Hsu*, National Taiwan University, Taiwan, Republic of China

Plasmas in saline solutions receive considerable attention in recent years. How the electrical power frequency influences the plasma behavior remains unclear. In this presentation, diagnostic studies of plasmas ignited in saline solution driven by an AC power source are presented. An AC power source with tunable frequencies between 50~1000 Hz and a voltage up to 600 V is used. The electrode at which the plasma is ignited uses a Pt wire 0.5 mm in diameter covered by a glass tube to precisely define the area exposes to the solution. Saline solutions with concentrations 0.01 M ~ 2 M are used. Diagnostic tools used include a voltage and a current probe to monitor the electrical characteristics. A high speed camera with a frame rate up to 1200 frames/sec is used to capture the bubble and plasma dynamics. An optical emission spectrometer and a photomultiplier tube are used to monitor the optical emission emanating from the plasma. It is shown that the plasma behavior is strongly coupled with the bubble dynamic adjacent to the electrode tip. Two distinct modes, namely the static mode and the jetting mode, are identified. In the static mode, a bubble with a diameter 1~ 3 mm is attached at the electrode tip for many seconds. The oscillation of the bubble is found to be relevant to the plasma behavior and is partially responsible to the stability of the discharge. This mode occurs mostly at the frequency below 100 Hz. The jetting mode occurs at a frequency higher than 300 Hz. In this mode, the plasma is ignited intermittently and is less stable comparing with the bubble mode. Under low applied voltages, bubbles of hundreds of μm in diameter are continuously jetted from the electrode tip. As the applied voltage increases, the micro-bubbles tend to coalescence into large bubbles and attach back to the electrode thus the switching of the above two modes is observed. Further increase in the applied voltage leads to bright plasmas with high current and severe

electrode damage occurs. It is also observed that under the applied voltage above 200 V, the plasma ignited in the negative half cycle of the power period shows a much stronger emission intensity than that in the positive half cycle. By the integration of the high speed image, the optical emission spectroscopy, and the electrical characteristics, the mechanism of the plasma formation under various frequencies and how it is affected by the bubble dynamics will be proposed.

10:00am **PS-FrM6 Solution Plasma Processing of Carbon Nano-Fillers in Ammonia Aqueous Solution for Preparation of Polymer Nano-Composite Materials**, ***T. Shirafuji***, *Y. Noguchi, J. Hieda, N. Saito, O. Takai*, Nagoya University, Japan

Solution Plasma Processing (SPP) has been performed in ammonia aqueous solution for amino functionalization of multi-walled carbon nanotubes (MWCNTs). The MWCNTs, which do not disperse in aqueous solution, have uniformly dispersed after the SPP. The treatment time for obtaining 10 g of the well-dispersed MWCNTs was only 2 hours. Infrared absorption spectroscopy of the SPP-treated MWCNTs revealed that NH_2 bonds were formed on the MWCNTs. The destruction of the MWCNT structure was not observed as shown by the characteristic Raman spectrum. The composite materials were prepared with the SPP-treated MWCNTs and polyamide 6 (PA6), and showed better tensile, bending and impact strength than those of non-treated MWCNTs and polyamide 6. Grafting of the ε-aminocaproic acids has been performed on the NH_2 sites of the MWCNTs. Appearance of the amide-I and amide-II bands in the infrared absorption spectrum of the grafted sample indicated that the grafting was successfully achieved. By grafting the ε-aminocaproic acids, which has the molecular structure of one segment of the PA6, we can expect hydrogen bonding between the N-H and O=C sites in the PA6 and grafted epsilon-aminocaproic acids, and can expect further improvement in mechanical strength of the PA6/MWCNT composites.

Authors Index

Bold page numbers indicate the presenter